national accelerator laboratory

TM-300
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A PROPOSAL FOR ACHIEVING 500 GeV OPERATION WITH THE 15-Ft. BUBBLE CHAMBER: Design of a Magnetized Muon Shield for the Neutrino Beam

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April 30, 1971

I. INTRODUCTION

The purpose of this note is to propose a magnetized iron muon shielding facility, to be installed in the neutrino beam. This facility will allow the increase of energy of the incident proton beam to 500 GeV on the primary target, so that neutrinos from the decay of the highest energy pions and kaons produced can be studied in the 15-ft. bubble chamber. The presently contemplated shielding stops muons only to about 350 GeV. With canonical assumptions, 400-GeV protons would produce 10^3 muons/m^2 per 10^{13} interacting protons in the fiducial volume of the bubble chamber. Thus present plans do not allow operation of the accelerator above perhaps 375 GeV for the production of wide-band neutrinos for bubble chamber study.

A brute force increase in muon range shielding to allow 500 GeV operation would add about 100 meters of iron to the berm. Such a shield would be about 3m square, and would contain 25 tons of iron per foot of running length. Its total mass would be about 8200 tons, and its cost over half a million dollars exclusive of installation costs. The alternative proposed herein will be cheaper by a factor of perhaps five. In addition, it can be tested without undue effort, expense, or interference with other work. We hope it will demonstrate how the present berm and bubble chamber laboratory set-up can still be used if the accelerator energy is raised at some future time to 1000 GeV. Scaling to 1000 GeV is out of the question for a brute-force range shield.

II. DESIGN CRITERIA

A description of the mode of operation of the proposed magnetized iron muon shield was given in a paper (Appendix I) to appear in the Proceedings of the 1971 International Accelerator Conference, (Muon Shielding for a 500-GeV Neutrino Facility, by Y. W. Kang, A. Roberts, D. Theriot, and S. L. Meyer). This paper used the earlier work of Theriot and others, based on the computer program of R. G. Alsmiller[1], to show how a muon shield could be designed of magnetized iron, which would be much shorter than an equivalent earth or iron absorption shield. The basic principle is simple; muons that would otherwise traverse the axis of the shield and strike a detector at the far end are deflected by magnetized iron, and thus miss the detector. They can be sufficiently deflected by much less iron than it takes to absorb them. The residual intensity due to the deflected beam can be estimated by using the Alsmiller algorithm for intensities off axis in semi-infinite shielding media. Various backgrounds due to muons scattering around the shield are also estimated in the above paper. They limit the amount of attenuation achievable.

III. DESIGN OF SHIELD

The muon shield consists of two portions: the magnetized iron deflector or lens, and an axial iron "plug". Their proposed location is shown in Fig. 1.

The deflector is a stack of soft iron about 3 meters square and 15 meters long. It is magnetized by an axial current, the return legs of the winding being outside the iron. The magnetization thus produced is toroidal, the flux lines being approximately circular and coaxial with the beam. Particles traveling more or less parallel to the axis are therefore, depending on their sign, deflected either outwards or inwards. The deflector is therefore a lens, converging for one sign, diverging for the other. In either case, the particles eventually diverge from the real or virtual focus. The highest energy muons present are deflected sufficiently to miss the axially located detector downstream.

The "plug" is a stack of unmagnetized iron 16" or so on a side, and 100 meters long. It is placed on the beam axis just upstream from the deflector.

The design criteria for the entire system are:

1. Particles that traverse the entire plug emerge with too little energy to penetrate to the bubble chamber area.
2. Particles that miss the plug are all deflected sufficiently by the magnetic field to give the required attenuation in muon flux at an axially located detector at the end of the shield.
3. Particles that enter the plug and are scattered out of it will either a) strike the magnetic deflector and be adequately deflected, or b) have too low an energy, if they miss the deflector, to reach the detector.

Magnetic Deflector

While it would be desirable to use a uniformly transversely magnetized block of iron as a deflector, the magnetization that can be obtained in a short sample is much too low, with any reasonable exciting current, to be useful. Thus we are forced to toroidal magnetization--the iron surrounded by a current-carrying conductor, to obtain flux lines whose entire path is in iron, and which require corresponding low magnetizing currents.

The deflector thus focuses the muons into a diverging cone. The fraction that is deflected downward or upward escapes further notice (except in the small region where the upward beam emerges from the ground). The lateral elements of the cone may give increased radiation intensities at ground level. Since the radiation is local, rapidly diverging, and not very intense, it is proposed to take no measures in advance, but to measure the intensity under operating conditions and take only those corrective steps (e.g. fencing) indicated.

Required Magnetization of Deflector

Figure 1 indicates the distances involved in the proposed layout; the distance from the deflector to the bubble chamber is 680 meters. From considerations like those of Fig. 4 of Ref. 1, we find that the required deflection angle to reach the required level of 10^{-13} muons/m^2 per interacting proton is 18 mrad, including a safety factor for multiple scattering. We assume a magnetization value B in the iron of 16 kgauss, for an energy of 378 GeV (the value at the center of the deflector for highest energy incident muon). We also want to allow for a maximum diverging angle of incident muons of 2 mrad. Thus we find that we must bend 378 GeV muons 20 mrad in 16 kgauss; this takes 15.75 meters or 51.6 ft. We round off to about 52 ft., and hope for 17 kgauss.

Design of Plug

The plug has two major effects. It slows down the muons that traverse it, and for all muons that are not scattered out of it, reduces their energy to the point that they do not reach the bubble chamber even if they traverse the deflector undeflected (on axis). On the other hand, most muons are scattered out of it, and are then subject to defocusing by the deflector. It is then necessary only to ensure that the scattered muons are sufficiently deflected by the magnetized iron lens to compensate for the additional outward deflection due to scattering from the plug. (This applies only to the converging case; for the diverging lens the additional scattering is helpful and increases the divergence of the beam.)

The mean scattering angle produced by the iron plug is proportional to the square root of the length traversed, while the loss of momentum, and thus the increased deflection in the lens, are linear in that quantity. There is therefore a minimum length above which the increased deflection will always exceed the scattering. For iron this length turns out to be about 20-30 meters over the entire momentum spectrum of interest. For lengths less than the minimum the escape probability of the scattered particle is low, and the scattering angle small, so that the deflection deficit produced by the scattering rarely exceeds one milliradian. Thus criterion 3a above is essentially satisfied.

Muons scattered out of the plug at so large an angle that they miss the deflecting lens are of too low an energy to reach the detector area; thus 3b is satisfied.

IV. INSTALLATION CRITERIA

In order to keep the cost of the shielding facility under $100K, it is necessary to avoid building and excavation costs wherever possible. Consequently, we would propose:

1. The 100-meter iron plug, consisting of about perhaps $15K worth of scrap, should be set on a footing that would avoid undue settling; it should be high enough to allow for

some settling; and it should require no enclosure, so that it will be directly buried by earth. This is necessary to preserve the integrity of the berm as a muon shield.

2. Since the cost of excavating the berm and refilling it over 100 meters of length would far outweigh the cost of the iron, it is important that the plug be installed before the berm is filled in.

3. The magnetized iron deflector or lens must itself also be buried in earth to preserve the shielding. However, we must provide for current to excite the coil and for removing heat. The construction of the lens will preclude servicing of the coil (except at the ends), other than by excavating and unstacking, which is formidably expensive. Consequently it seems desirable to fabricate the coil so that all welds and joints are at the two ends. Since the coil is just over 50 ft. long, this appears practical.

Despite the absence of a building, water cooling of the coil is feasible because the earth cover will keep the temperature range above freezing. Forced air cooling presents another alternative. No final design has yet been reached.

It will be highly desirable to provide an enclosure ten feet square and perhaps ten feet long at the ends of the lens, to allow for the installation of counting and monitoring equipment. Since the shield is located within a few feet of building E-102, this should be neither difficult nor expensive.

4. Again, an adequate footing for the 1250-ton lens must be provided; a reinforced concrete pad will be satisfactory.

IV. MAGNETIZING COIL

The coil contains about 4.5 tons of copper, and requires about 130 kw for operation at a field to provide an estimated 17 kgauss in the iron, assuming stacking that leaves 1/4" gaps between blocks. If the stacking gaps can be reduced to 1/8", the required power will drop by a factor of two.

V. LIST OF MATERIALS AND SERVICES REQUIRED; COST ESTIMATE

If we assume the use of the Rochester cyclotron iron for the major portion of the deflecting lens, and the use of the present stockpile of 12" x 12" iron billets, stacked 2 x 2 to make a two-foot square cross-section, for the plug, then we find that the major remaining costs are for additional iron and for the coil and power supply. The costs are estimated in Appendix II. They assume no costs for excavation; i.e. the plug at least, and preferably the lens as well, to be installed before the berm is filled in. The expense of excavating and refilling the berm for the plug, which is 100 meters long, would nearly double the total cost of the facility. Excluding this, a very rough minimal cost estimate is around \$100K.

R. G. Alsmiller, M. Leimdorfer and J. Barish, ORNL-4322 (1968).

APPENDIX I.

MUON SHIELDING FOR A 500-GEV NEUTRINO FACILITY

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Summary

The explicit problem considered is the amount and "shape" of muon shielding required for a neutrino experimental area operated with a primary proton beam of energy up to 500-GeV. Muon transport programs have been developed for NAL[1] which permit the calculation of muon intensities within a semi-infinite homogeneous medium. Results of such a calculation for a neutrino facility indicate that an earth shield 1100 meters in length and 7 meters in radius is required to permit the use of a bubble chamber detector with a primary beam energy of 500-GeV. A new calculational method using only available programs is proposed which permits the quantitative estimation of the effect of a magnetized-iron deflector. Results from this technique show that a magnetized-iron block 1.5 meters in radius and capable of deflecting the highest energy muons by 22 mrad may permit the use of a shield which is adequate for bubble chamber operation but only 550 meters of earth in length at 500-GeV.

Introduction

The basic features of a neutrino facility are shown in Figure 1. A primary proton beam strikes a target T producing pions and kaons. These secondary hadrons pass through a decay tunnel or drift space of length L where they decay to neutrinos. The proton beam and the hadrons are "stopped" at the end of the decay tunnel in a beam stop. For the purposes of later discussion the beam stop is preceded by a "disc" of radius R. The same pions and kaons whose decay produces neutrinos also produce high energy muons. The beam stop is followed by a massive shield to reduce the muon flux to tolerable levels in the detector area downstream of the beam stop by a distance x. The total space available for the facility is the length L + x. For a given available space we wish to maximize L and minimize x in order to maximize the neutrino flux at the detector always subject to the constraint that the charged particle (muon) flux at the detector is low enough for personnel safety (10^5 muons/m^2-sec which is 1.3 mrem/hr) and bubble chamber operation (roughly four orders of magnitude better: 1 muon/m^2-pulse).

Calculation

Computer programs have been developed[1] which permit the calculation of the intensities of muons in a semi-infinite homogeneous medium produced by a given spectrum of incident muons using the theory of Eyges[2] to include the effects of multiple coulomb scattering with collision energy loss. The hadron production has been calculated using the Trilling formula with the current parameters[3]. All results will be expressed in terms of muons/m^2-interacting proton but for comparison with the requirements stated it should be noted that the assumption is that 10^{13} protons may interact per pulse in the neutrino area target. The calculations have assumed a decay tunnel 600 meters in length and 0.5 m in radius and use total collision energy loss without radiation loss and without subsequent straggling correction. We rely on the observation of Roe[4] that a suitable combination of collision loss and direct pair production energy loss chosen so as to exhibit small fluctuations (and so obviate straggling corrections) is equivalent to use of the total collision energy loss alone if one starts with 500-GeV muons.

Earth Shield

Results for the case of an earth shield only follow straightforwardly and are shown in Figure 2. The curves show that an earth shield 1100 meters in length and 7 meters in lateral extent suffice to permit the use of bubble chamber detectors at 500-GeV.

Hybrid Shields

We enumerate three effects which contribute to the net muon flux at the detector and note that this analysis is applicable to two types of hybrid shields: magnetized-iron-deflection-plus-earth shields as well as earth-plus-iron-plug. The geometry of interest is shown in Figure 1. We consider that the "disc" at the end of the decay tunnel represents either a magnetic deflector or an iron plug.

1) Muons are emitted within an angular range $\theta \leq \theta_1$ where $\tan \theta_1 = r/L$ and strike the disc at a radius less than or equal to r. These muons pass through no material before the disc and hence are all transported through the disc. They may thereafter scatter but we refer to this muon contribution as TRANSMISSION (I) only. These muons are characterized by large energies since they are produced at forward angles and we must reduce the flux of these muons by deflecting them away from the detector or by ranging them out with a combination of earth and iron.

2) Muons produced with angles $\theta_1 \leq \theta \leq \theta_2$ where $\tan \theta_2 = R/L$ would, if propogated along straight lines, strike the disc at radii greater than r and less than or equal to R. These muons, however, must pass through a length of earth shielding medium which varies between zero and (approximately) L (1-r/R). Muons in this region can make two kinds of contribution to the net muon flux at the detector since they can scatter and pass around the disc (and scatter back to the detector) or pass through the disc. The muons which pass through the disc make a contribution to the net muon flux similar to that of I and we call this contribution TRANSMISSION (II). The muons which scatter around the disc may make a contribution GROUNDSHINE (II).

3) Muons produced at angles greater than θ_2 will in general produce only a contribution to the flux by passing around the disc. This contribution is GROUNDSHINE (III). Muons from this third production region can also scatter and pass through the disc contributing TRANSMISSION (III).

There is little point to reducing one contribution if another is larger. In all cases, there is no reason to reduce the muon flux to a level below that produced by neutrino interactions in the shield themselves producing muons. There is a natural point of diminishing returns. From a simple viewpoint, the transmission muons are treated with either magnetic deflection or ranging in iron while the groundshine muons are ranged out in earth. Qualitatively, as the radius of the disc is increased, the groundshine muons become less in intensity and, more importantly, softer in energy. The groundshine muons are thus ranged out in smaller earth shields for larger disc radii. The radius of the disc is thus a parameter to vary.

The contribution of TRANSMISSION (I) is straightforwardly calculated. The contribution of TRANSMISSION (II) has been overestimated by assuming that all muons produced in the (II) angular region are transmitted through the disc. The Alsmiller program suffices to calculate TRANSMISSION (I) and TRANSMISSION (II). The contribution of TRANSMISSION (III) is neglected since the muons from region III are in general of lower energy than those in the other regions and we shall thus assume that these muons are readily removed by magnetic deflection and/or direct ranging in iron. The contribu-

...ion of GROUNDSHINE (III) is likewise readily calculable by the Alsmiller program. The program does not, however, lend itself to a calculation of GROUNDSHINE (II) since the geometry for this is not homogeneous. The contribution GROUNDSHINE (II) has been calculated using a Monte Carlo program for the case of a disc 1.5 meters in radius. We are indebted to Kyu Lee for this calculation which indicates that GROUNDSHINE (II) makes no contribution at all for any earth shield in excess of 550 meters long.

Figure 3 shows that the on-axis GROUNDSHINE (III) muon flux after an earth shield of 550 meters is reduced to 10^{-13} for a disc radius of 1.5 meters.

Figure 4 shows isoflux curves for TRANSMISSION (I) plus (an overestimate of) TRANSMISSION (II) and the 10^{-13} on-axis intensity at an earth shield length of 550 meters if the disc produces a deflection of 22 mr.

The conclusion of this numerical example is that a magnetized iron block 1.5 meters in radius and capable of deflecting region I muons by 22 mr may permit the use of a shield as short as 550 meters of earth for a bubble chamber detector and 500-GeV incident protons. Likewise, an iron plug 200 meters in length followed by 350 meters of earth will suffice to range out region I muons. In either case, therefore, an overall shield length of 550 meters is possible for bubble chamber operation at 500-GeV. This compares with the previous figures of 1100 meters for a full earth shield.

For more details, reference should be made to NAL Reports TM-259, TM-263 and TM-267.

References

1. R. G. Alsmiller, M. Leimdorfer and J. Barish, ORNL-4322 (1968)
2. L. Eyges, Phys. Rev. 74, 1534 (1948)
3. NAL Report FN-193 (1969)
4. B. Roe, University of Michigan, Private Communication

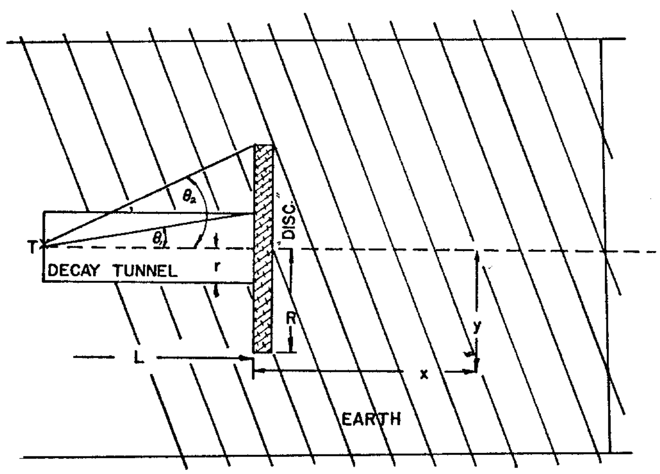


FIGURE I GEOMETRY OF NEUTRINO FACILITY

FIGURE 2
TRANSMISSION - PLUS - GROUNDSHINE ISOFLUX CURVES; NO MAGNETIC DEFLECTION
DECAY TUNNEL 600m LONG, 0.5m RADIUS

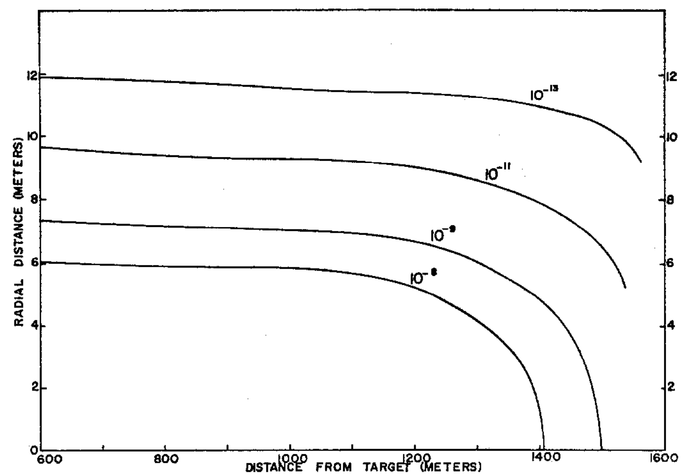


FIGURE 3 GROUNDSHINE (III)

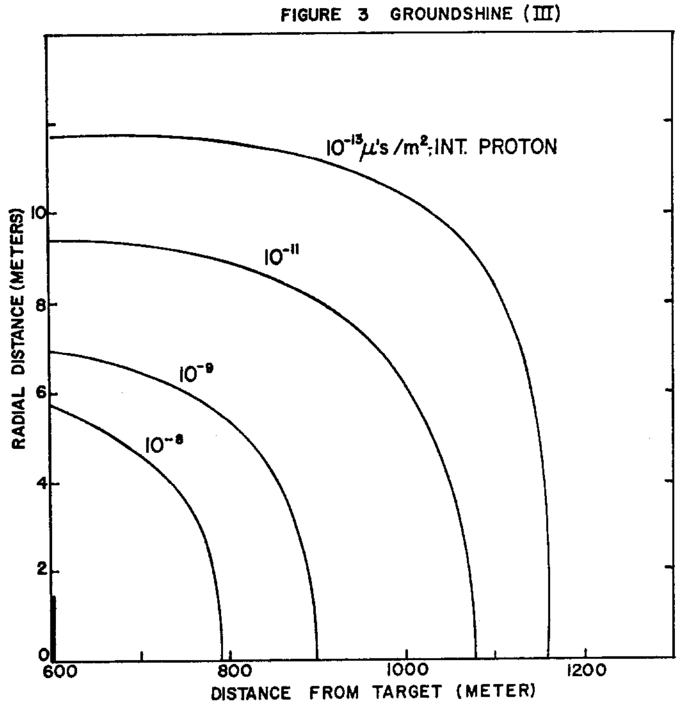
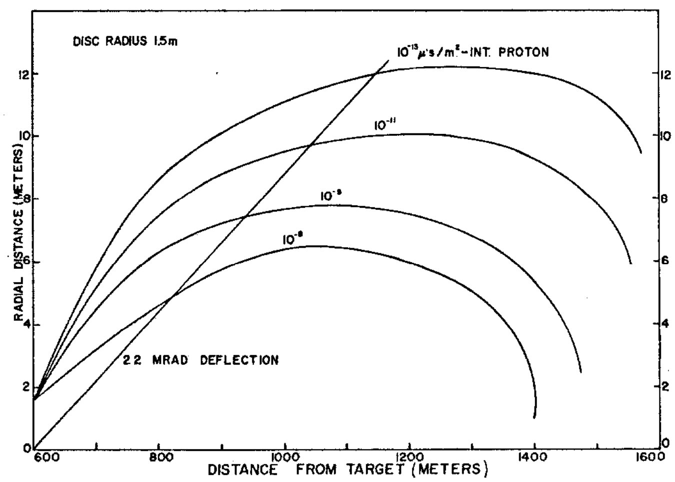


FIGURE 4 ISO FLUX CURVES FOR TRANSMISSION(I)-PLUS (AN OVERESTIMATE OF)-TRANSMISSION(II)



APPENDIX II Cost Estimate

Item		Cost (thousands)
I.	Deflecting Magnet.	
	a. Rochester Cyclotron magnet iron, delivered to site	-
	b. Additional iron to bring length up to 50 ft. 300 tons of flat plates, 6 to 12" thick, flame cut to size. Delivered at $70./ton, plus $12.50/ton for cutting	24.6
	c. Central plug for magnetic lens 31.5 tons 7" x 13" flame cut, at $82.50/ton	2.6
II.	Plug.	
	Use one-foot-square, 20-ft. long billets now stacked at railroad siding. Stack 2 ft. by 2 ft., 320 ft. long. 64 billets required (if purchased, would use 16" x 18" cross-section, 160 tons, which would come to $13.2K)	-
III.	Coil.	
	a. 9000 lbs. copper, at $3/lb, fabricated	27.0
	b. Power supply, 150 kw	10.
	c. Controls, wiring, plumbing, etc.	3.0
IV.	Footings.	
	a. Plug: 3 ft. x 320 ft. = 1000 $ft.^2$	1.5
	b. Deflecting lens: 12 x 60 ft. = 720 $ft.^2$	1.0
V.	Excavation.	
	None required, if installed before berm erected.	-
VI.	Two rooms, 10 x 12 x 12 ft., one at each end of lens, connected by short corridors to E - 102. No utilities	2.0
VII.	Rigging.	
	a. 1300 tons, deflecting magnet	
	b. 300 tons, plug	
	c. Coil insertion	(Guess: 15.0)
	Total	86.7
+ 15% contingency, escalation		99.5

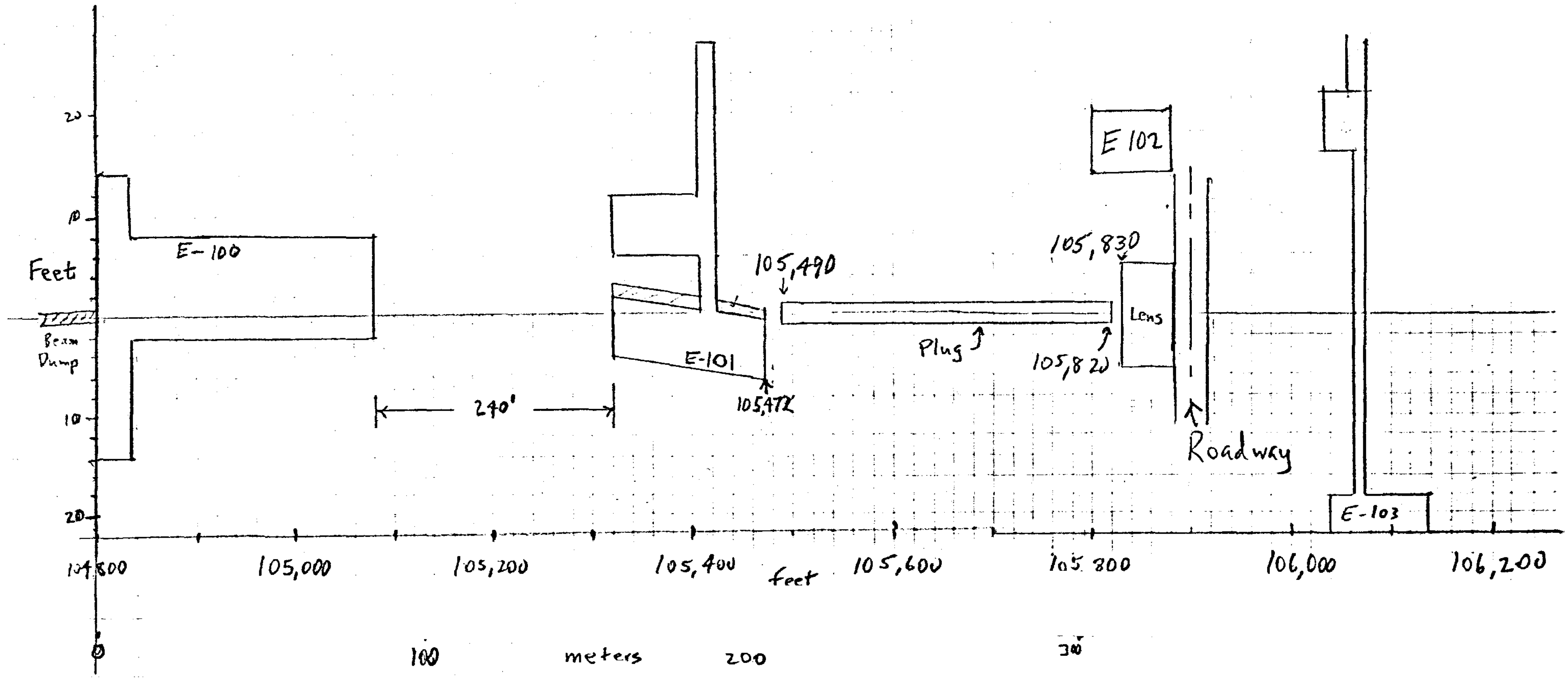


FIG. 1 Proposed Location of Plug and Lens in Neutrino area

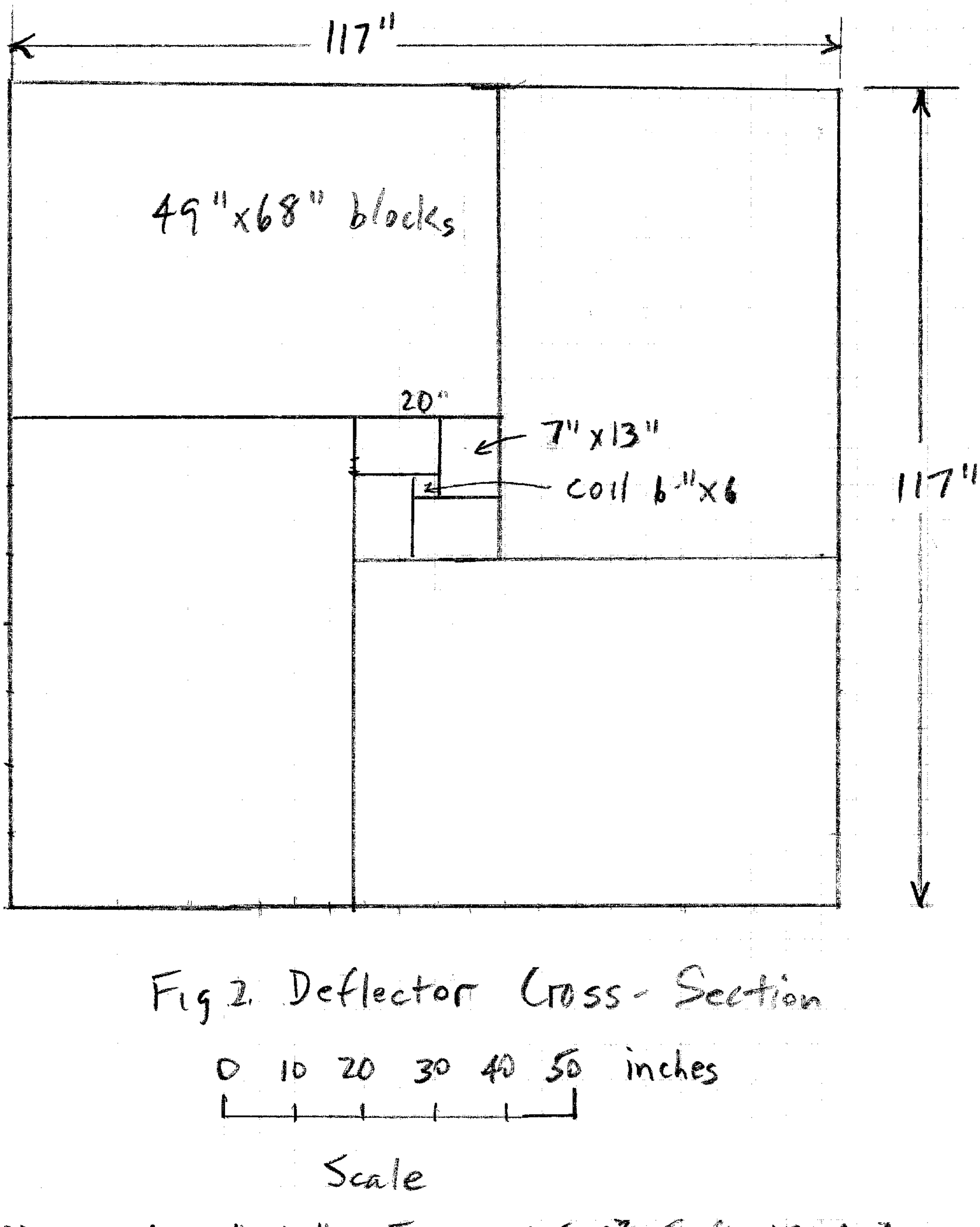


Fig 2. Deflector Cross-Section

Central Plug: $4 \times 7'' \times 13'' \times 50\ ft = 2.53\ ft^2 \times 50\ ft = 126\ ft^3 =$ 31.5 tons

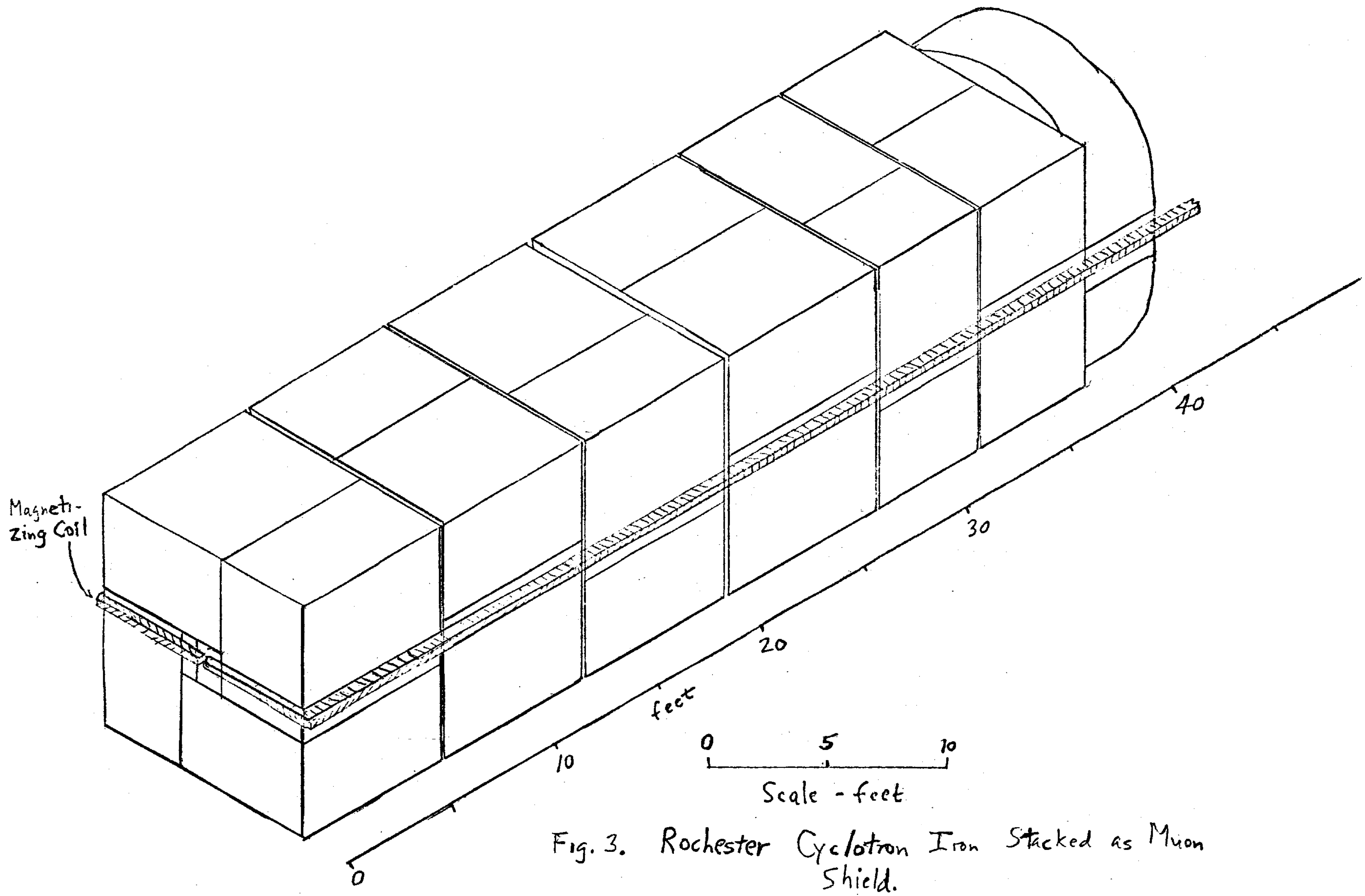


Fig. 3. Rochester Cyclotron Iron Stacked as Muon Shield.